Evaluation of ^{86}Kr Cross Sections for Use in Fusion Diagnostics

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The National Ignition Facility at Lawrence Livermore National Laboratory uses ^{86}Kr as a diagnostic tool to measure the neutron flux produced by fusion reactions. As krypton is chemically inert, it can be included directly in the fuel capsule, and the neutron reaction products can be measured to determine the flux of fusion neutrons. Also, the ^{86}Kr(n,2n)^{85}Kr reaction can be used to study the important ^{85}Kr branching point in the slow neutron capture process in stars. Several experiments have been performed to directly measure the cross sections of the neutron-induced reactions on ^{86}Kr. In this work, performed at the National Nuclear Data Center at Brookhaven National Laboratory, experimental data on the total, neutron production, radiative capture and inelastic scattering cross sections in ^{86}Kr were used in conjunction with the fast region nuclear reaction code EMPIRE and a new resonance region evaluation to produce a new evaluation of the ^{86}Kr cross sections. The EMPIRE calculations used the Koning-Delaroche global spherical optical model potential with a slight deformation. The (n,2n) reaction cross section used this model with the addition of the multi-step compound and multi-step direct pre-equilibrium reaction models. To fit the radiative capture data, the direct and semi-direct capture mechanisms were included by adding the cross sections with the compound capture cross section calculated by EMPIRE. The inelastic scattering de-excitation of the two lowest lying excited states were modeling accurately by including an approximation of the dynamic deformation of the soft rotator model. The data on the de-excitation of the higher levels allowed for the spin and parity assignments of several levels to be determined. With the correct physical models and nuclear structure, the theoretical cross sections matched the data very well, and this new evaluation will be incorporated in the next release of the Evaluated Nuclear Data Files library and will allow for more accurate neutron flux calculations for the ^{86}Kr diagnostics.

^{86}Kr Applications

- **Krypton is a chemically inert gas that has applications in fusion diagnostics and astrophysics.** ^{86}Kr is added into the fuel capsules at the National Ignition Facility (NIF) and reacts with the fusion neutrons. The product nuclei of the radiative capture and (n,2n) neutron interactions can then be radiochemically analyzed to determine the neutron flux that was produced [Heller, "A New Detector for Analyzing NIF Experiments," Science and Technology Review, Lawrence Livermore National Laboratory, Dec 2012].
- **^{85}Kr is an important branching point in the slow neutron capture process in stars**, but is short-lived and is not easy to access experimentally [Raut, *et al*. Phys. Rev. Let. **111**, 112501 (2013)]. The ^{86}Kr(n,2n)^{85}Kr reaction can provide insight into the accuracy of the current modeling of the ^{85}Kr reactions.

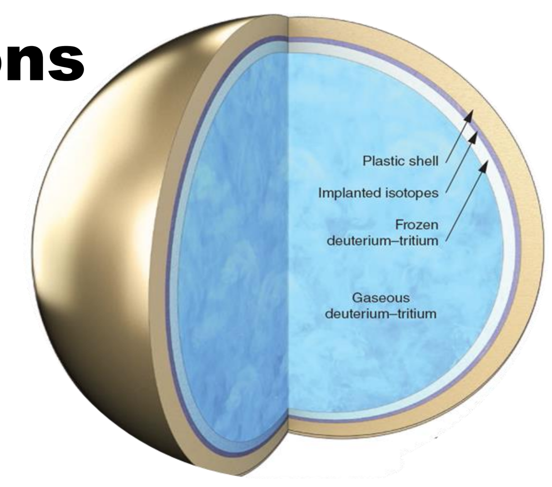
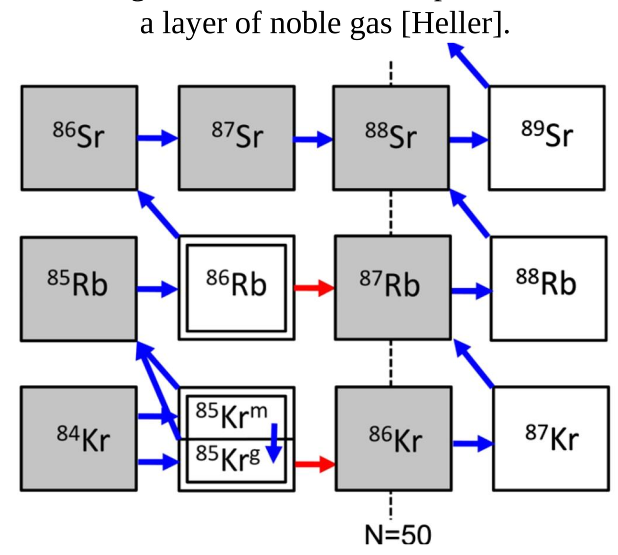


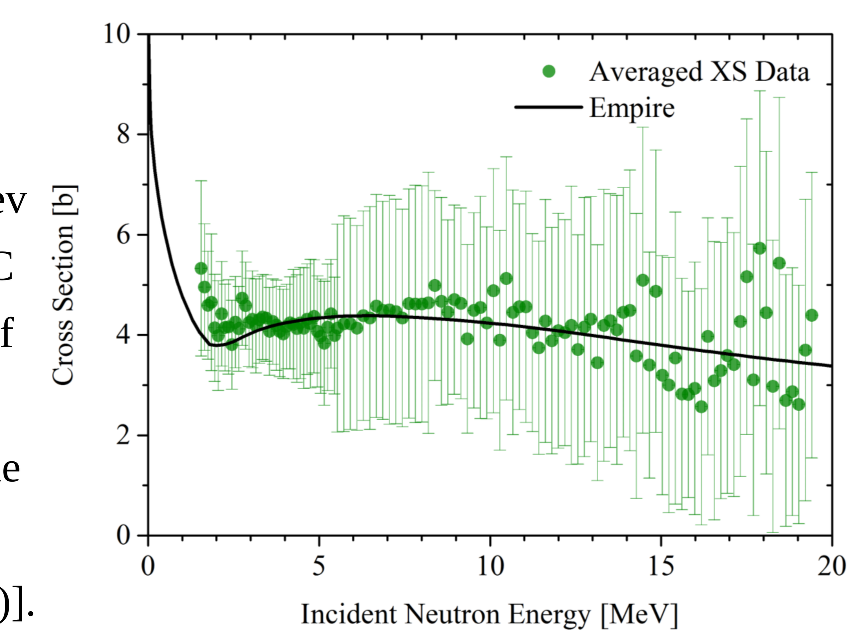
Diagram of the NIF fuel capsule with a layer of noble gas [Heller].



Branching diagram of the s-process showing how ^{85}Kr can either undergo beta decay to become ^{85}Rb or neutron capture to become ^{86}Kr [Raut].

Total Reaction Cross Section

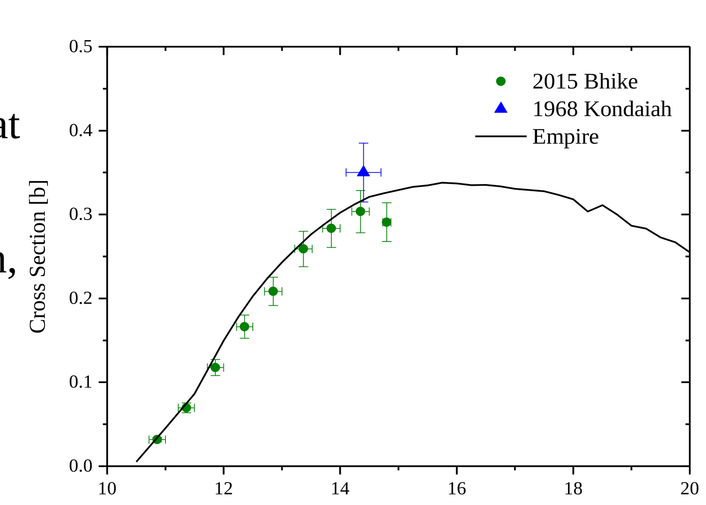
- The total reaction cross section is the easiest quantity to measure and so provides the most accurate data.
- The total cross section was measured at the Oak Ridge Electron Linear Accelerator in 1983 [Raman, *et al.*, Phys Rev C **28** (1983)] and again in 1988 [Carlton, *et al.*, Phys. Rev. C **38** (1988)]. These data sets were energy averaged because of the large amount of data.
- The nuclear reaction code EMPIRE was used to calculate the theoretical cross sections based on Hauser-Feshbach theory [Herman, *et al.*, Nuclear Data Sheets **108**, 2655-2715 (2007)].
- EMPIRE was run with a Koning-Delaroche spherical optical potential [Koning, *et al.*, Nucl. Phys. A713 (2003)] with a slight deformation.
- The calculated total cross section is the summation of all other calculated reactions and so the comparison to the data is a check of the optical model parameters and all reaction models used, and fits the averaged experimental data above 1 MeV, where the optical model is valid.



Total reaction cross section as calculated by EMPIRE and the averaged experimental data sets.

Neutron Production Reaction

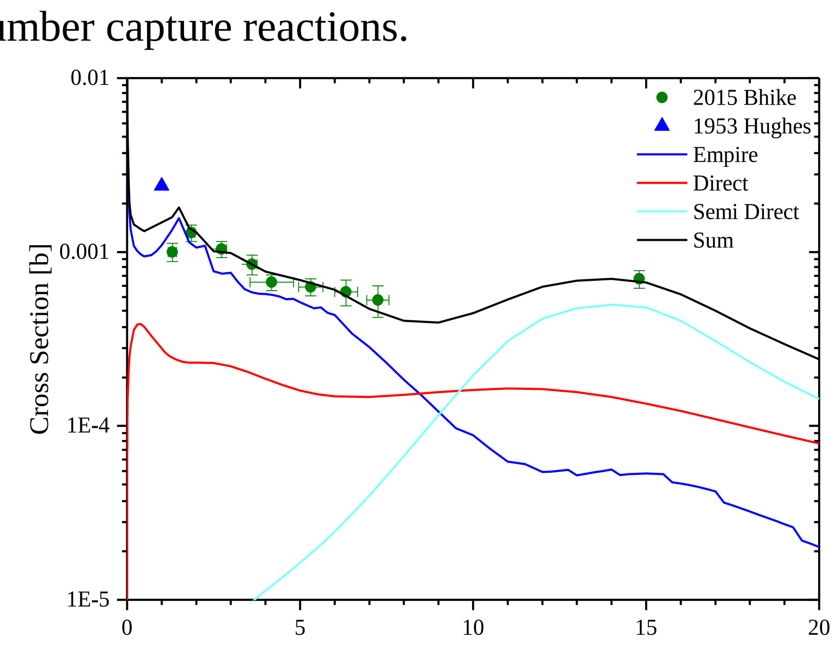
- The ^{86}Kr(n,2n)^{85m}Kr reaction is important for understanding the ^{85}Kr branching point. It is also one of the reactions used at NIF, as the decay of the isomer can be measured easily.
- Experimental data is available for the ^{85}Kr isomer production, from TUNL [Bhike, *et al*., Phys Rev C **92,** 014624 (2015)] and the Georgia Tech 200 keV accelerator [Kondaiah, *et al.*, Nuclear Physics A120, 0375-9474 (1968)].
- Multi-step direct and multi-step compound pre-equilibrium reaction models were used in the theoretical calculation, and the EMPIRE calculated (n,2n) isomer reaction cross section matched the data very well.



(n,2n) isomer reaction cross section as calculated by EMPIRE and the data from TUNL [Bhike] and Georgia Tech [Kondaiah].

Radiative Capture Reaction

- The ^{86}Kr(n,γ)^{87}Kr reaction is also used as a NIF diagnostic, as the decay of ^{87}Kr produces a convenient γ-ray that can be used to determine the number capture reactions.
- Radiative capture measurements were made at TUNL [Bhike] and at Argonne National Laboratory [Hughes, *et al.*, Phys Rev **78,** 632 (1950)].
- Radiative capture in this energy region can occur through compound, direct, or semi-direct mechanisms. EMPIRE models only the compound portion of this, under the assumption that it is the dominant mechanism.
- The direct and semi-direct capture cross sections for ^{86}Kr were calculated following the method outlined by Chiba *et al.* [Chiba, *et al.*, Phys Rev C **77**, 015809 (2008)].
- For the evaluation, the direct and semi-direct cross sections were added to the compound cross section calculated by EMPIRE and the resulting sum fits the experimental data well.



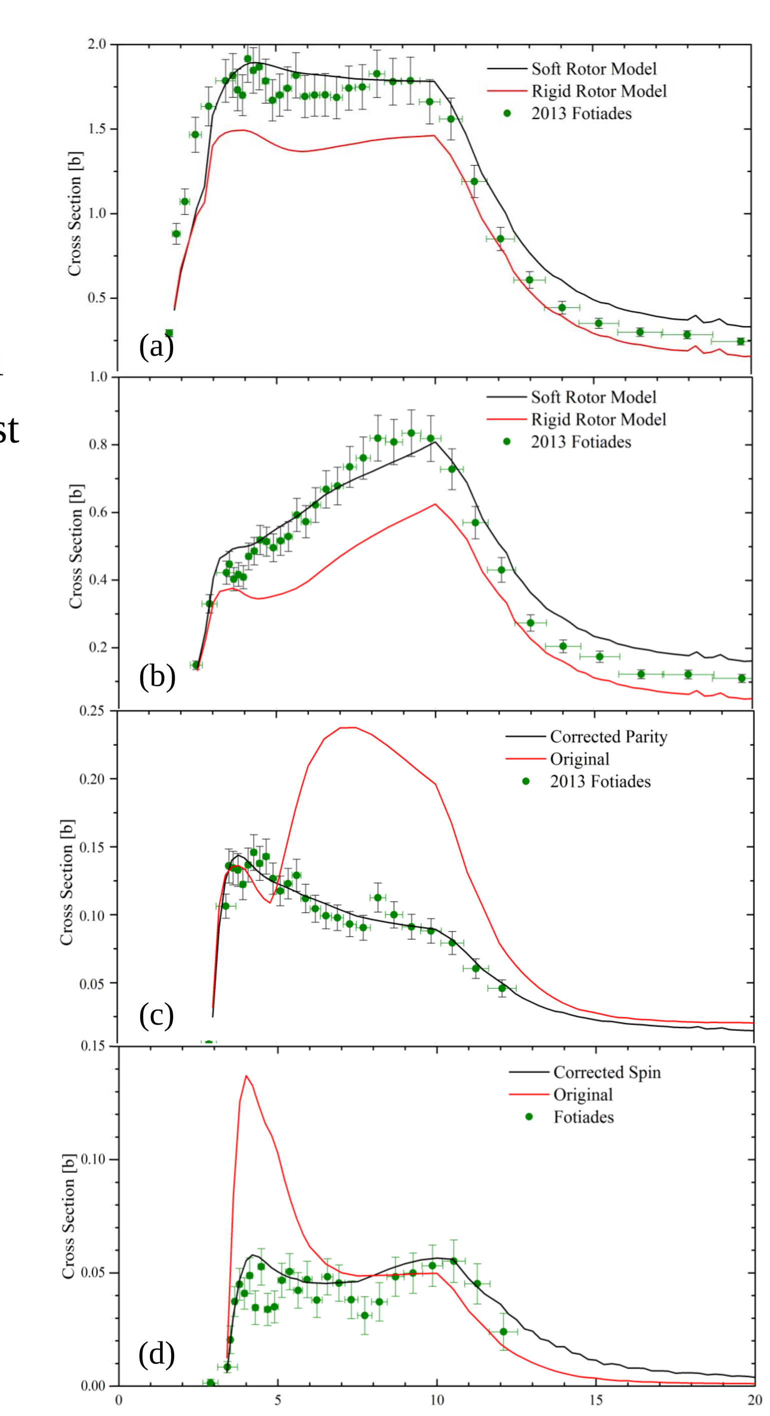
Radiative capture cross section as calculated by EMPIRE, and the experimental data from TUNL [Bhike].

Inelastic Scattering Reactions

- Inelastic scattering partial gamma decay data gives insight into the nuclear structure of the target nucleus.
- The partial gamma cross sections were measured at the Los Alamos Neutron Science Center's Weapons Neutron Research (LANSCE WNR) facility in 2013 [Fotiades, *et al.*, Phys Rev C **87** (2013)].
- EMPIRE was used to calculate the cross section of each partial gamma decay using the coupled channels method for the lowest three levels, and the Distorted Wave Born Approximation (DWBA) for higher levels.
- The coupled channels calculation uses the rigid rotator model, which assumes that all nuclear levels are uniformly deformed. However, the soft rotator model, which accounts for the dynamic deformation of the levels based on the spin, is a more accurate model. The inputs for the soft rotator model are not available for ^{86}Kr so the effects of the soft rotor model were approximated with level-dependent deformations.
- The decays from several of the higher levels, treated with DWBA, had the wrong shape in energy. This was due to incorrect spin or parity assignments in the original EMPIRE calculation. Revised values are:

Level	Original J^π	Final J^π
7	3^-	3^+
9	1^+	2^+
11	3^+	4^+
12	0^+	1^+
13	2^+	4^+

- With the inclusion of the dynamic deformation and the corrected structure, the calculations of the inelastic scattering partial gammas matched the experimental data very well.



Cross sections for four of the partial gammas as calculated by EMPIRE and measured at LANSE [Fotiades]. Plot (a) shows the decay of the first excited state to the ground state, and (b) the decay of the second excited state to the first. Both were improved by using the dynamic deformations. Plot (c) shows the decay of the sixth excited state to the second excited state, which was improved by changing the parity assignment, and (d) shows the decay of the tenth excited state to the first excited state, which was improved by changing the spin assignment from 3 to 4.

Conclusions

- Several new models were included in the evaluation to better match the experimental data. The direct and semi-direct capture mechanisms improved the radiative capture calculated cross section, the pre-equilibrium models improved the (n,2n) reaction cross section, and the inclusion of the soft rotator dynamic deformations improved the inelastic scattering partial gamma cross sections.
- Several levels in the original EMPIRE calculation had incorrect spin or parity assignments, and the correction of these improved the fit of the calculated cross sections to the partial gamma data.
- The final evaluation, with these changes, fits the experimental data very well and will be included in the ENDF/B-VIII.0 library.

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